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The Role of Prevalent Wind on the Geomorphic Development of the Marine-Marginal Zone of the Mahanadi Delta, India

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Abstract

The marine-marginal zone of the Mahanadi delta is arcuate and runs parallel and adjacent to the present-day shoreline. Based on the various geomorphic features of this zone, three subregions are differentiated: the southwestern part, in which the vast stretch of land is characterized by extensive coastal sand bodies along with an eolian dune cover; the middle part, characterized by numerous, discontinuous and parallel to subparallel series of ancient beach ridges separated by tidal flats, creeks or swamps; and the northeastern part dominated by tidal flats and mangrove swamps.

Prevalent wind has played a significant role in the development of these geomorphic features. In the southwestern part, the shore stretches against the prevalent wind direction, and wave and eolian processes are dominant. Thick and extensive eolian sand bodies have covered not only frontal beach ridges but also a low-lying delta plain behind the coast. The shoreline trend in the middle part is almost parallel to the wind direction, giving rise to strong longshore currents which, combined with waves, form linear sand bodies parallel to the shoreline. The northeastern part is shadowed from prevalent winds. Wave and longshore processes are minimal there, tidal forces are prominent and hence, extensive tidal flats and swamps are developed.

Key words : delta, geomorphology, longshore current, Mahanadi, marine-marginal zone, prevalent wind, tide, wave

Introduction

Deltas result from interacting fluvial and marine processes. In a marine-marginal transition zone of a delta, various geomorphic features are formed due to a complex interplay of these processes. Differences in relative intensity of the processes acting in this zone cause variability of geomorphology, which ultimately governs morphodynamic development and facies organization of deltas (Wright and Coleman, 1973; Galloway, 1975; Coleman, 1976; Galloway and Hobday, 1996). Marine agents acting on deltas include waves, tides, longshore currents and oceanic currents. Among them, waves and tides are generally regarded as the principal agents and variability of deltas is commonly explained in terms of the relative balance between fluvial, wave and tidal processes (Galloway, 1975; Bhattacharya and Walker, 1992; Reading and Collinson, 1996; Galloway and Hobday, 1996). Some workers stress the important role of longshore currents as one of the delta forming processes (Coleman, 1976; Wright, 1978; Coleman and Prior, 1980).

It is true that delta morphology is largely dependent upon the relative balance between fluvial and marine processes. The relative intensity of these processes may not be equal all along a delta coast but may show significant regional differences within a delta, giving rise to differential geomorphic developments within a delta. The role of prevalent wind

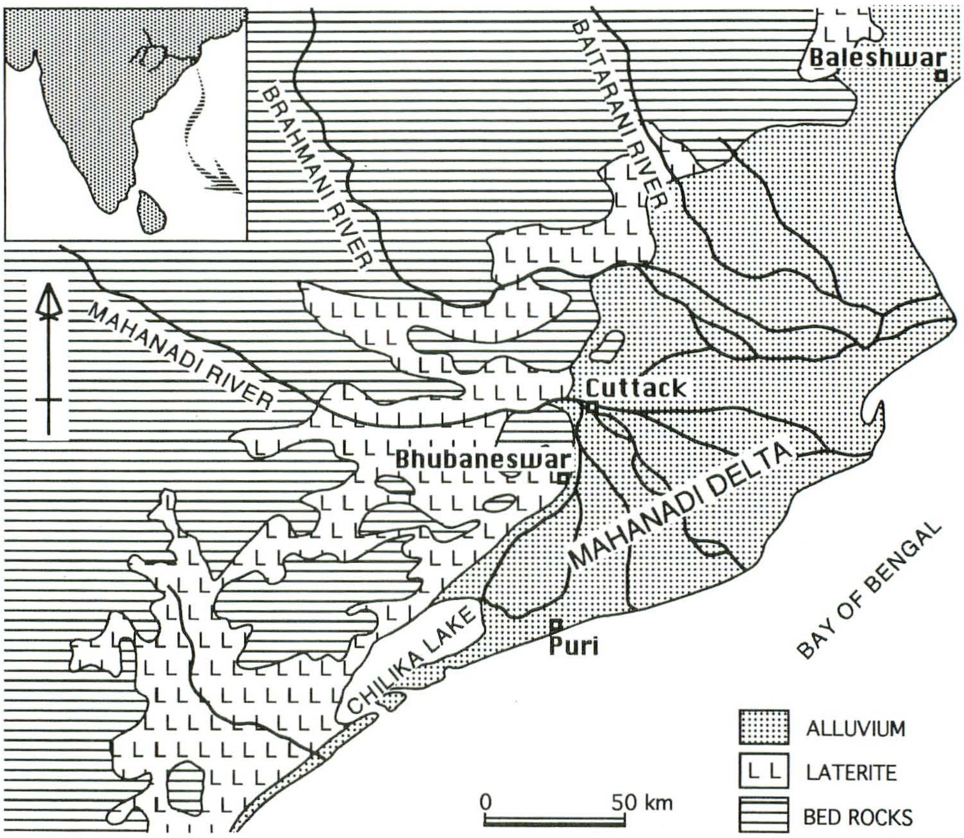

Fig. 1 Sketch map showing the location of the Mahanadi delta.

across the coast in association with other marine forces has also some control on the development of geomorphic features. This paper deals with the geomorphology of the marine-marginal zone of the Mahanadi delta on the east coast of India (Fig. 1) and brings out the role and control of prevalent wind on the geomorphic development of the delta.

Regional Setting and Outline of Mahanadi Delta

The river Mahanadi, about 850 km long and having a catchment area over 142,000 km^2, debouches into the Bay of Bengal to the east of Cuttack, Orissa State and has formed a prominent delta, the Mahanadi delta, on the east coast of India (Fig. 1). The delta covers an area of about 9,000 km^2. It is bounded on the northeast by the river Brahmani and on the southwest by Chilika lake. The Mahanadi delta has a maximum width of about 140 km (Figs 1, 2).

Below the delta head to the west of Cuttack, the main Mahanadi channel divides into the Mahanadi on the north and the Kathjodi on the south. These two further divide downstream into many branches, which presently make up four active distributary systems (Fig. 2). They are, from north to south: the Birupa system, the Mahanadi system, the Kathjodi-Debi system, and the Kuakhai system (Mahalik et al., 1996; Maejima and Mahalik, 2000). The water flow during the monsoon months (July, August, and September) constitutes 85 to 90 percent of the annual yield of the Mahanadi river and its distributaries (Mahalik and Acharya, 1986), and the delta plain is thus prone to floods during these months. Besides the present-day active distributary channels, several dead or defunct channels are noticed on the delta plain (Fig. 2). The abandoned channels were once prominent distributary channels, forming distributary systems like present-day active ones. These are, designated from northeast to southwest: the Sukhbhadra, the old Kathjodi, the Burdha, the Alaka, the Prachi, and the Ratnachira systems (Mahalik et al., 1996; Mahalik, 2000; Maejima and Mahalik, 2000).

The seaward margin of the delta plain is marked by a continuous sandy beach of the shoreline (Fig. 2), which is a consequence of wave and longshore current activities along the delta coast. A southerly wind is inferred to be responsible for the generation of waves and littoral drifts along the coast. Waves are shown

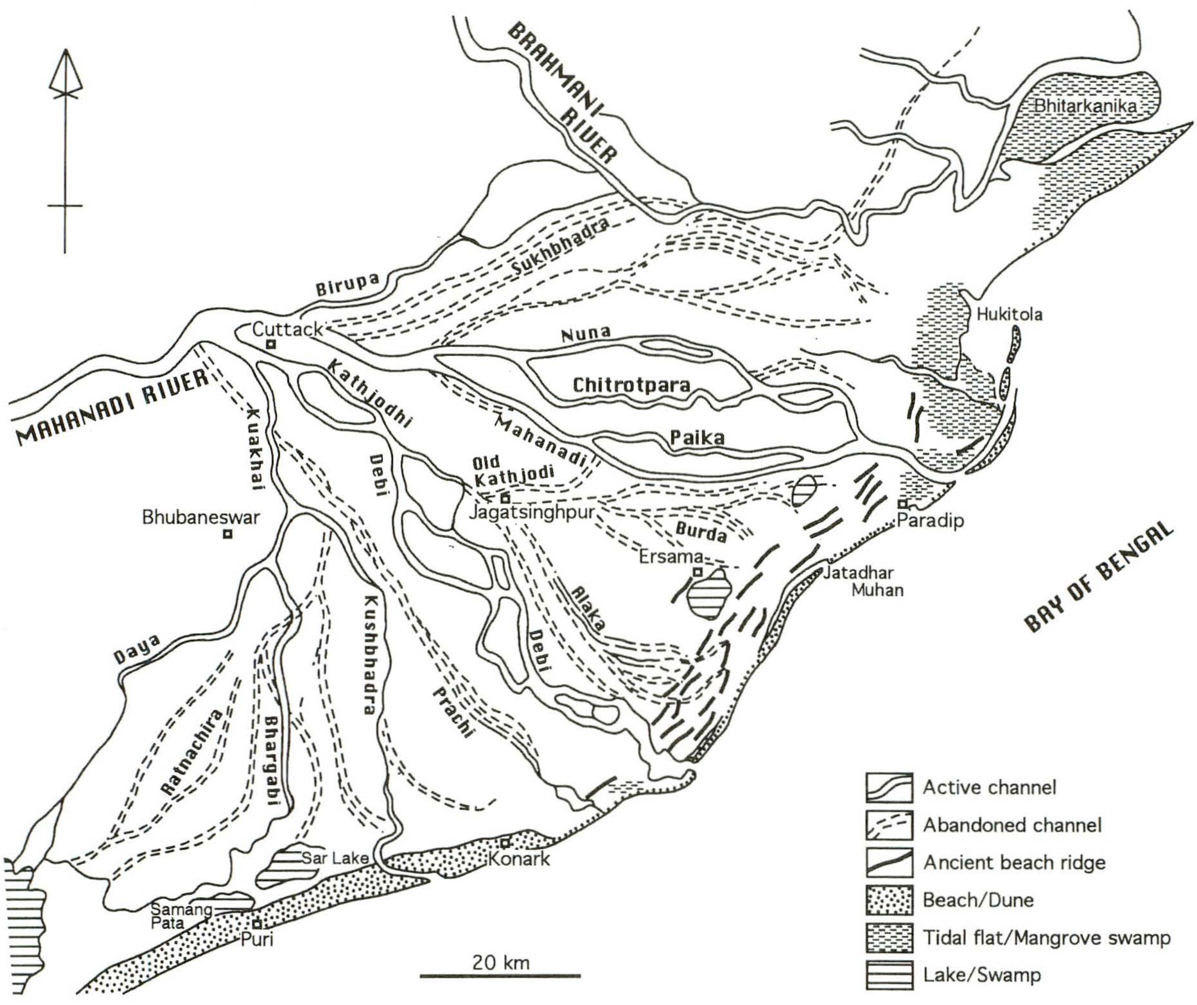

Fig. 2 Geomorphic features of the Mahanadi delta.

to be predominantly from south or southwest (Varadarjulu and Harikrishna, 1979). Waves commonly have a height of less than 1.25 m and a period of less than 7 sec. During storms, however, waves reach 4 to 5 m in height. A southerly prevalent wind tends to generate northward-flowing strong longshore currents along the coast. Consequently net northward littoral drifts occur all along the shore of the delta, resulting in significant northward deflection of channel courses close to the coast before they debouch into the sea (Mahalik et al., 1996; Maejima and Mahalik, 2000), as well as producing bars and spits along the delta coast (Fig. 2). Tidal ranges are two to three meters; and tides are also an important agent in the Mahanadi deltaic coastline, particularly on the northeastern part where tidal flats and swamps are developed.

Geomorphology of Marine-Marginal Zone

Downstream of the delta head, the distributary channel system fans out and ultimately meets the sea at several discharge points. Both the riverine forces and marine forces act to distribute sediments carried by the river Mahanadi from its hinterland (Fig. 1). The result is the growth of a vast deltaic plain, encompassing the features produced by fluvial, marine and mixed processes, which have been evolving through the Late Pleistocene to Holocene period. The Mahanadi deltaic plain is subdivisible into two major regions: the upper, fluvial sector and the lower, marine-marginal sector (Mahalik et al., 1996; Maejima and Mahalik, 2000). The marine-marginal sector is a significant geomorphic belt, 10 to 20 km wide, running parallel and adjacent to the present-day shoreline (Fig. 2). The various geomorphic features of this part of the delta plain are of marine, fluviomarine and eolian origin, including beaches, spits, beach ridges, dunes, tidal flats, and mangrove swamps. These geomorphic features are unevenly distributed within this belt. Based on the presence of the dominant geomorphic feature, three subregions are differentiated within the marine-marginal zone of the delta plain. These are: southwestern part from Chilika lake to the Prachi river mouth region; central part between the rivers Prachi and Mahanadi; and northeastern part occupying the area north of Mahanadi river.

Southwestern part dominated by sand bodies with eolian dune cover

From Chilika lake at the southwestern extreme of the delta through Puri-Konark to the river mouth region of Prachi, the vast stretch of land is characterized by extensive coastal sand bodies with sand dunes on them (Fig. 2). The sand bodies are 2 to 5 km wide and stretch for more than 50 km along the coast. They are as much as 15 m high, standing as barriers to deltaic drainage and causing water logging behind them. At present there exist remnants of two large water bodies, Sar lake and Samang pata. Artificial cuts are created through this sand barrier to drain water from the ill-drained areas behind. The coastal sand bodies are made up of clean and well-sorted, wind-blown sands covering the muddy deposits of a tidal flat or swamp origin as well as the beach ridges.

Central part dominated by beach ridges

In the region between the rivers Prachi and Mahanadi, the marine-marginal zone is characterized by the occurrence of numerous ancient beach ridges (Fig. 2). These are discontinuous, more or less dissected, low, sandy ridges running parallel or subparallel to each other, produced mainly by wave action parallel to ancient shorelines. Individual ridges are up to 2 m high above the muddy delta plain and are several kilometers long. The ridges farthest from the coast lie around Ersama (Fig. 2), about 15 km away from the present-day shoreline. The ancient beach ridges have played an important role in controlling the drainage pattern in the marine-marginal zone of the delta, where the drainage is more or less parallel to the coast. The swales between adjacent ridges are occupied by localized tidal flats and swamps. Some of the swales, specifically those close to the shore, have a connection with the sea at their northern end and form narrow and elongated, lagoon-like shallow depressions filled with seawater. A typical example of such a water body, 1 km wide and as much as 15 km long, lies to the east of Ersama and is known locally as Jatadhar Muhan (Fig. 2). A similar feature is also present near the mouth of the Debi river.

Northeastern part dominated by tidal flats

The northeastern part of the Mahanadi delta (north of Paradip, Fig. 2) is characterized by low-lying, flat and moist plains. Here are few positive topographic features like beach ridges and dunes, which are characteristic in the central and southwestern parts of the marine-marginal zone. In this region, the prominent Hukitola spit extends for more than 20 km northward from the mouth of Mahanadi river and makes its inner side embayed (Fig. 2). Swamps occupy the extensive area around Hukitola bay and Bhitarkanika.

Discussion

Within the marine-marginal zone of the Mahanadi delta, characteristic geomorphic features significantly differ from area to area, giving rise to segmentation of the marine-marginal zone. In the southwestern part, the vast stretch of land is occupied by the extensive coastal eolian sand bodies. The central part is characterized by numerous, discontinuous ancient beach ridges running parallel or subparallel to each other. The northeastern part is dominated by extensive tidal flats and mangrove swamps along with embayments of the sea. Such a differential development of geomorphic features within the marine-marginal zone can be attributed to a complex interaction of various factors. Among them, prevalent wind and wind-governed marine agents, waves and longshore currents, are most likely the principal contributors to the regional differentiation of marine-marginal geomorphology (Fig. 3).

The shoreline in the southwestern part runs at a large angle against the direction of the south to southwesterly prevalent wind (Figs. 2, 3). Waves tend to attack the shore almost directly, not much obliquely, because wave direction is closely related to the direction of prevalent wind. Consequently wave processes are most significant along the shore of this part of the delta (Fig. 3). Longshore currents flowing towards the east also operate along the shore, but their intensity is relatively low. Fluvial influences are minimum in this part of the delta. Sediment-reworking by waves, coupled with the subordinate role of longshore currents, is responsible for the generation of beaches of a linear shoreline in this part of the marine-marginal zone. Through the wave-rework processes, shore materials formed beach ridges which progressively stacked to form linear sand bodies. At the same time, eolian activity is also intense along the this part of the coast as the shoreline trend is almost normal to the prevalent wind direction. Sands of beaches and stack-

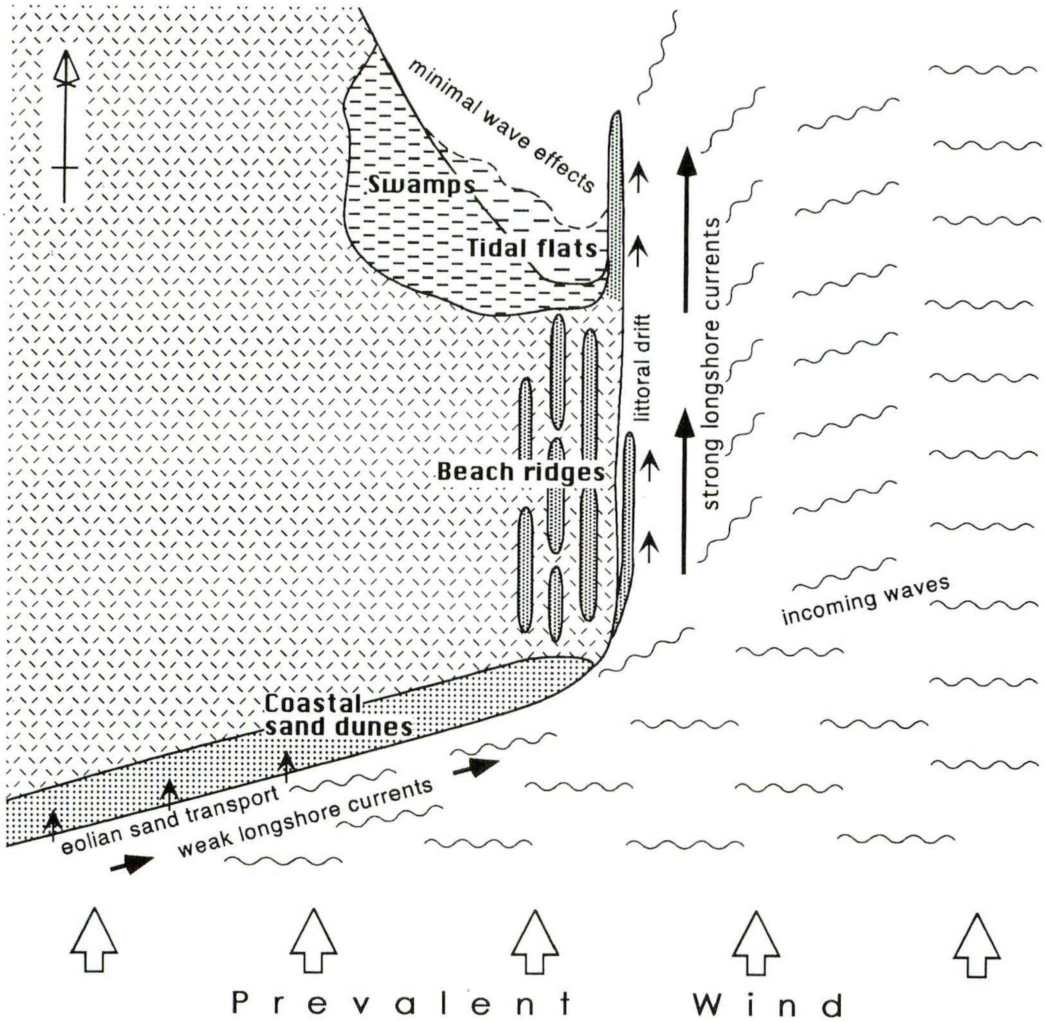

Fig. 3 Schematic model for the geomorphic development of the marine-marginal zone of the Mahanadi delta.

ed beach ridges are further reworked by wind and develop into sand dunes. Wind-blown sands covered not only beach ridges but also the low-lying delta plain behind the coast, resulting in thick and extensive eolian sand bodies along the coast. Surya (Sun) Temple at Konark was built on the then shore in the middle of the 13th century. It is now located about 3 km inland from the present-day shoreline but was mostly buried in dune sands before the start of excavation in the early twentieth century. This is a good and concrete example demonstrating seaward shoreline advance and thick accumulation of eolian sands on beach ridges and on the delta plain during the last seven hundreds years.

In the central part of the marine-marginal zone, the shoreline trend is nearly parallel to the southerly to southwesterly prevalent wind direction (Fig. 2). Consequently, strong longshore currents flowing towards the northeast are generated along the coast of this part. Sediment brought to the distributary channel mouths and debouched into the sea is significantly reworked by longshore currents as well as by waves, forming spits and longshore bars parallel or subparallel to the shoreline specifically near the mouths of distributary channels (Fig. 3). Sediment reworking is enhanced by the influences of fluvial outflows which are active only during the monsoon months. Prominent spits are found at the mouths of the Mahanadi and Debi rivers (Fig. 2). The development and extension of spits and bars towards the north at the channel mouths due to northeasterly moving littoral drift have constantly pushed the channel mouths towards the north. The resultant channel courses show significant right turns towards the north, parallel to the shoreline for some distance before debouching into the sea (Fig. 3). Such a northward bend in channel courses near the

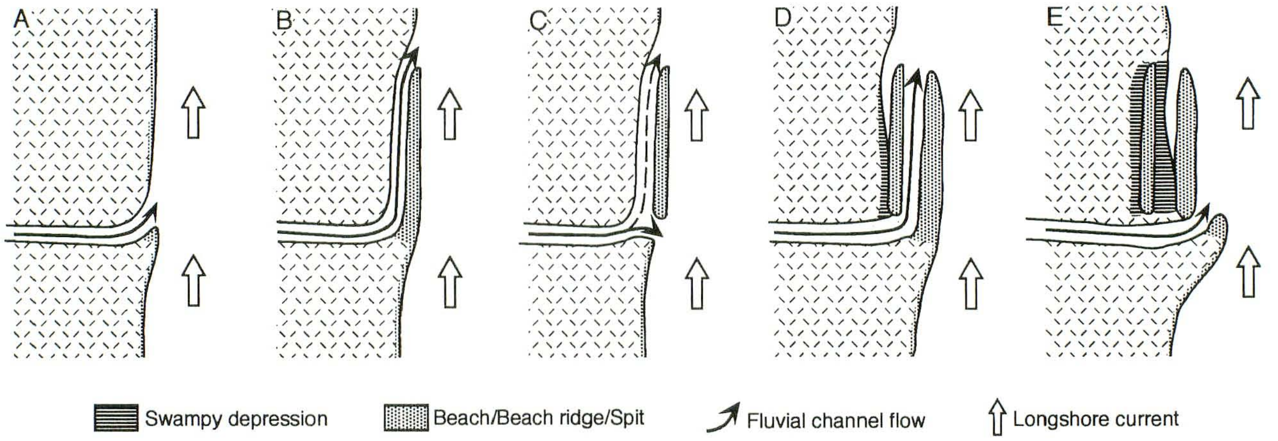

Fig. 4 Schematic model for the formation of numerous, parallel- to subparallel-aligned, linear beach ridges separated by swampy depressions, typical in the central part of the marine-marginal zone of the Mahanadi delta. (A) Northward-flowing, strong longshore currents result in a spit at the mouth of a distributary channel. (B) Extension of a spit cause deflection of a channel course parallel to the shoreline and pushes the channel mouth to the north. (C) During high flood stages, a channel cuts across a spit and a channel mouth opens there to the sea. The former course of a channel becomes inactive with time and is ultimately abandoned. (D) At the active channel mouth, a new spit grows and extends to the north, resulting in deflection of a channel. (E) Repetition of channel-cutting and new growth of spits result in the marine-marginal zone characterized by numerous beach ridges separated by linear swampy depressions.

mouth is evident not only in present-day active channels but also in many of abandoned channels on the delta plain, providing one of the criteria estimating the position of ancient shorelines of the Mahanadi delta (Mahalik, 1991, 2000; Mahalik et al., 1996). Longshore currents have thus been playing an important role in the geomorphic development of the sea-marginal zone in the middle sector of the delta margin since then. Spits obstructing and bending channel courses are not so resistant to erosion by channel flows. It is observed that during cyclones and high flood seasons spits get eroded and are cut across by channels, thereby flowing directly to the sea. Spits may also be washed and cut from the sea-side by intensive storm waves. The Hukitola, a spit that formed at the river mouth of Mahanadi, has now been cut at several places, reducing it to several island-like features (Fig. 2). During floods, the most significant erosion of a spit tends to occur at its connecting part to the land, that is, at the point of northward deflection of a channel. Hence, a channel cuts across a spit and directly opens to the sea. A former channel course becomes inactive with time and is ultimately abandoned. As the channel mouth opened as a result of cutting of a spit, a new spit grows due to northward littoral drift. With extension of a spit, a channel deflects again toward the north and runs parallel to the shoreline. Through repetition of these processes, spits and abandoned channels have been progressively accreted seaward in the central part of the marine-marginal zone of the delta (Fig. 4). Consequently the central region of the marine-marginal zone is characterized by numerous, discontinuous, ancient beach ridges separated by elongated swampy depressions.

The shoreline of the northeastern part of the marine-marginal zone of the delta is dislocated to the west from the northern extension of the shoreline of the central part and runs northerly (Fig. 2). The shore of this part is, thus, shadowed from the southerly to southwesterly prevalent wind. Wind-governed marine agents, waves and consequent longshore currents, act much less intensely along the shore compared with the other parts of the delta coast (Fig. 3). Hukitola spit, extending from the mouth of Mahanadi river, further reduces the effects of waves and longshore currents by sheltering its inner side from open-marine wave activities. Accordingly, sediment reworking by waves, littoral currents and winds is minimal along the shore of this part of the marine-marginal zone. Under such a low-energy condition, tidal flats and mangrove swamps have developed extensively.

Conclusions

The marine-marginal zone of a delta is formed under a complex interaction of marine and fluvial agents. The principal marine agents are waves, tides and longshore currents. In the Mahanadi delta, these marine agents have played an important role in the formation of the marine-marginal zone of the delta plain. The regional differences in characteristic geomorphic features within the marine-marginal zone of the Mahanadi delta apparently reflect differences in the relative intensity of these agents at work. In addition, the primary controlling factor, which is prevalent wind, should be noted. Prevalent wind generally governs activities of waves and longshore currents, as well as its own eolian activity, in the coastal zone. Along the Mahanadi delta coast, there exist significant differences in the intensity of sediment dispersal processes caused by wave, longshore current and eolian activities, according to the shoreline trend relative to the direction of prevalent wind. The resultant geomorphic features show uneven distribution within the marine-marginal zone of the delta. In the southwestern part, the shore stretches against the prevalent wind direction, and wave and eolian processes are dominant. Thick and extensive eolian sand bodies have covered not only frontal beach ridges but also a low-lying delta plain behind the coast. The shoreline trend in the central part is parallel to subparallel to the direction of prevalent wind, giving rise to strong longshore currents. Longshore currents, combined with waves, have contributed to the development of discontinuous, parallel to subparallel, linear sand bodies of a beach ridge origin separated by swampy depressions of abandoned channels. The northeastern part is shadowed from prevalent winds. Wave and longshore processes are minimal there, and the extensive tidal flats and swamps have been developed.

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